# REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188



**1. AGENCY USE ONLY** *(Leave blank)*

**2. REPORT DATE**

**3. REPORT TYPE AND DATES COVERED**
Final 30 Sept 91 - 30 Mar 95

**4. TITLE AND SUBTITLE**
Microwave & Millimeter Wave Magnetic Solitons & Chaos in Magnetic Thin Films & Thin Film Superlattices

**5. FUNDING NUMBERS**
ARO Grant Number:
DAAL03-91-G-0327

**6. AUTHOR(S)**
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**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
ARO 29375.18-PH

**11. SUPPLEMENTARY NOTES**
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**12a. DISTRIBUTION / AVAILABILITY STATEMENT**
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**13. ABSTRACT** *(Maximum 200 words)*
The objectives of this program were (1) the experimental and theoretical investigation of microwave magnetic envelope (MME) solitons, (2) the application of Brillouin light scattering (BLS) techniques to the study of nonlinear magnetic excitations in magnetic films, (3) the use of BLS techniques to understand the magnetic properties of magnetic thin film sandwiches and multilayers, and (4) the microwave/millimeter wave characterization of hexagonal ferrite materials. One personal objective was to reestablish a U.S. presence in (2) and (3). A wide variety of MME soliton phenomena were observed experimentally and modeled theoretically, including backward volume wave, forward volume wave, and surface wave dark solitons, multiple solitons, and soliton collisions. BLS techniques were used to characterize the critical modes for subsidiary absorption, parallel pumping, and resonance saturation spin wave instability processes in thin magnetic films. BLS techniques were also used to study magnetic excitations in Fe/Cr/Fe samdwich films as a function of field orientation and scattering configuration. The low power loss properties of hexagonal ferrite materials were characterized from 10 to 100 GHz.

19950703 327

**14. SUBJECT TERMS**
Solitons, microwave magnetics, ferrites, magnetic thin films, spin waves, magnetostatic waves, magnetic multilayers, millimeter wave magnetics, yttrium iron garnet thin films

**15. NUMBER OF PAGES**
13

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | UL |

Colorado State University

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# Microwave & Millimeter Wave Magnetic Solitons & Chaos in Magnetic Thin Films & Thin Film Superlattices

## FINAL REPORT

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**Date of report: May 31, 1995**

**ARO PROPOSAL NUMBER: 29375-PH**
**ARO GRANT NUMBER: DAAL03-91-G-0327 P00005**

**GRANT PERIOD: 30 September 1991 - 30 March 1995**

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# RESEARCH RESULTS

## A. Problem Statement

The objectives of this ARO program were (1) the experimental and theoretical investigation of microwave and millimeter wave magnetic envelope solitons, (2) the application of Brillouin light scattering (BLS) techniques to the study of nonlinear magnetic excitations in magnetic films, and (3) the use of BLS techniques to understand the magnetic properties of magnetic thin film sandwiches and multilayers, and (4) microwave/millimeter wave characterization of hexagonal ferrite materials. One personal objective of the work was to reestablish a U.S. presence in (2) and (3).

## B. Summary of Results

### 1. Microwave Magnetic Solitons in Thin Films

**Numerical modeling**: A theoretical study of soliton profile solutions to the nonlinear Schrödinger (NLS) equation was completed. The results demonstrated several key features of spin-wave envelope solitons: (1) propagation at amplitude dependent velocities other than the linear wave group velocity, (2) characteristic soliton properties when the dispersion and nonlinear response satisfy the Lighthill criteria, and (3) increased pulse decay rate in the nonlinear soliton regime.

**Dipole-Exchange Mode Properties:** In preparation for soliton measurements, work was also done on the magneto-exchange mode resonance spectra for the thin yttrium iron garnet films to be used for soliton generation. This work revealed structure in the"main mode" usually associated with the uniform precession resonance which was comprised of both a volume mode and a surface mode component. The spectra could be fitted by a dipole-exchange model based on standing waves across the film dimensions. This work resolves the long standing controversy over spectra interpretation between Sparks and Wolfram and deWames.

**Soliton Measuring System:** For the soliton measurements, a special microstrip delay line system was designed and constructed for use in the 6 GHz frequency range. The system employs a microwave synthesizer, a fast semiconductor microwave switch, a TWT amplifier, a delay line transducer structure, and a microwave transition analyzer for signal detection and analysis. The system has been used to study backward volume wave solitons, dark surface wave solitons, and forward volume wave solitons in yttrium iron garnet (YIG) thin films.

**Backward and Forward Volume Wave Solitons:** The backward volume wave (BVW) solitons for in-plane magnetized films satisfy the Lighthill criterion for soliton propagation. These modes have in-plane wave vectors which are parallel to the dc magnetic field and hence along the long direction of the long narrow YIG film strip used for the experiments. The observation of BVW solitons required a reasonably large magnet gap with the dc field and placement of the transducer structure in-line with the field in the gap. It was possible to make quantitative measurements of single and multiple soliton profiles by varying the input microwave power at fixed pulse width and by varying the input pulse width at fixed power. The results could be correlated with the various characteristic times for propagation, dispersion broadening, decay due to relaxation, and nonlinear response. Numerical modeling based on the NLS equation yielded profiles which were in fair agreement with experiment but showed several important discrepancies as well. These discrepancies indicate the importance of nonlinear damping in the soliton propagation processes. A similar program of measurements and modeling were carried out for forward volume wave solitons, in a configuration with the dc magnetic field perpendicular to the YIG film.

**Dark Solitons:** The use of a so-called "dark" input pulse, essentially a cw carrier signal which is turned off for 10-20 ns or so to form the "dark" signal, made it possible to observe dark solitons with the YIG film biased in the magnetostatic surface wave configuration with the in-plane dc magnetic field and the propagation direction perpendicular rather than parallel. The dark soliton profiles were in good agreement with theory and exhibited the characteristic 180° phase shift expected for dark solitons.

**Multiple Soliton Thresholds:** On the basis of the above results, further studies of the threshold powers required to produce multiple solitons was carried out. Here, the dependence of the threshold power for the nonlinear response which leads to eventual soliton formation on pulse width led to a critical experimental test of soliton theory. The data support the prediction that (1) the thresholds vary as the inverse of the square of the input pulse width and (2) the thresholds also scale with the number of solitons $n$ according to a factor $(2n-1)^2$.

**Soliton Collisions:** Work was also done on soliton collisions in both BVW and FVW configurations. The experiments were done by taking advantage of the near perfect reflection properties of properly prepared film edges for the pulses. It was possible to verify the basic property in which two soliton pulses pass through each other with no change in shape. In the BVW case, a peculiar wake effect was also observed. Here, the first soliton pulse was found to have a definite and reproducible effect on the shape of the second soliton, even without collision. The soliton collision work was a collaborative effort with scientists from the St. Petersburg Electrotechnical University, supported in part through a NATO Linkage Grant.

## 2. Brillouin Light Scattering (BLS) on Nonlinear Magnetic Excitations

An additional objective of the program was to apply Brillouin light scattering to the study of nonlinear spin wave processes in thin films. As part of this effort, Dr. Ming Chen and Professor Patton authored a chapter on spin wave instability processes which appeared in *Nonlinear Phenomena and Chaos in Magnetic Materials* in 1994. Considerable experimental and theoretical work was also done on spin wave instability processes in thin films: (1) A comprehensive theory of first order processes for thin films. (2) Measurements and analysis for the effect of different field configurations and film shapes on the thresholds and critical modes in subsidiary absorption. (3) Brillouin scattering characterization of the wave number and propagation angle distributions for the critical modes which are excited above threshold. (4) A detailed study of the fine structure associated with parallel pumping in YIG films magnetized perpendicular to the film plane.

In (1) and (2), all of the basic questions concerning spin wave instability in single crystal ferrite materials appear to have now been answered. A key result is that the density of states for the standing modes across the thickness and the lateral dimensions of the film has dependences on propagation angle and wave number, in combination with a theory which includes clusters of coupled modes, appears to explain all measurements to date. This represents a significant breakthrough in the understanding of spin wave instability processes.

In (3), it is found that the critical mode magnons above threshold do not follow the standard theoretical predictions of Suhl and Schlömann. Rather, the wave number distributions can be quite broad. It is clear from these results that the number of coupled modes which participate in instability processes can be quite large. This result is consistent with the more detailed results found in (1) and (2).

In (4), the standing mode nature of the critical modes for parallel pumping in in-plane magnetized films was firmly established. The results show, in addition, a useful way to determine the exchange stiffness parameter for thin films from parallel pumping experiments.

### 3. Brillouin Light Scattering (BLS) on Multilayers

The existing Fabry-Perot interferometer was upgraded with redesigned optics and a special antivibration stage to make a state-of-the-art multipass-tandem system with extremely high contrast, high photon counting sensitivity, and low noise. Measurements were carried out on giant magnetoresistance (GMR) multilayer thin films which demonstrate the nature of the high frequency magnetic excitations in such films. The measurements could be correlated in a quantitative manner with both the magnetization processes in the films and calculated mode dynamics. It was possible to show that the BLS spectrum for sandwich films is a very good indicator of the micromagnetic processes which define the magnetic ground state under given field conditions. One can see details in the magnetic transitions which are poorly defined, at best, by other techniques.

### 4. Other Work Accomplished

As an extension of the successful work on multilayers, the BLS technique was also applied to the problem of new phases for magnetic film materials, namely, fcc cobalt. This work has led, in turn to a new examination of the role of magnetocrystalline anisotropy in high frequency thin film magnetics

Measurements of the off resonance low power losses in hexagonal ferrite materials for millimeter wave applications was completed. The results indicate that the intrinsic ferromagnetic resonance linewidths in these materials are in the 0.6 Oe/GHz range, compared to 0.05 Oe/GHz for single crystal YIG. Such materials, with improvements, are candidates for millimeter wave soliton devices and multilayer films in the future.

### 5. Future Plans

The grant for the current program ended on September 30, 1994 and was granted a no cost extension through March 30, 1995 to allow for the completion of the work. A renewal proposal on "Microwave Magnetic Thin Film Soliton Device Physics" was submitted to the ARO on August 1, 1994. The ARO has indicated an intent to fund this work for three years with a start date of June 15, 1995. This work will extend the fundamental soliton work described above to the area of real device concepts and novel signal processing techniques which parallel the recent explosion in fiber optics and optical soliton communications technology.

## C. List of Publications

### 1. ARO Program Related Publications:


1. "Subsidiary Absorption Spin Wave Instability Processes in Yttrium Iron Garnet Thin Films, Critical modes, and the "Kink" Effect," G. Wiese, P. Kabos, and C. E. Patton, J. Appl. Phys. **74**, 1218-1228 (1993).

2. "Microwave Magnetic Envelope Dark Solitons in Yttrium Iron Garnet Films," M. Chen, M. A. Tsankov, J. N. Nash, and C. E. Patton, Phys. Rev. Lett. **70**, 1707-1710 (1993).

3. "High Field Effective Linewidth and Eddy Current Losses in Moderate Conductivity Single Crystal M-type Barium Hexagonal Ferrite Disks at 10 - 60 GHz," J. R. Truedson, K. D. McKinstry, P. Kabos, and C. E. Patton, J. Appl. Phys. **74**, 2705-2718 (1993).

4. "Numerical Study of Nonlinear Schrödinger Equation Solutions for Microwave Solitons in Magnetic Thin Films," M. Chen, J. M. Nash, and C. E. Patton, J. Appl. Phys. **73**, 3906-3909 (1993).

5. "Frequency Dependence of the Ferromagnetic Resonance Linewidth and Effective Linewidth in Manganese Substituted Single Crystal Barium Ferrite," R. Karim, S. D. Ball, J. R. Truedson, and C. E. Patton, J. Appl. Phys. **73**, 4512-4515 (1993).

6. "Spin Wave Instability Processes in Ferrites," M. Chen and C. E. Patton, in *Nonlinear Phenomena and Chaos in Magnetic Materials*, ed. P. E. Wigen, World Scientific Publishing Company, Ltd., Singapore, 1994.

7. "High Field Effective Linewidth and Eddy Current Losses in Moderate Conductivity Single Crystal Zn-Y Hexagonal Ferrite at 10 - 35 GHz," J. R. Truedson, P. Kabos, K. D. McKinstry, and C. E. Patton, J. Appl. Phys. **76**, 432-442 (1994).

8. "Parallel Pumping Fine Structure at 9.4 GHz for In-Plane Magnetized Yttrium Iron Garnet Thin Films," G. Wiese, L. Buxman, P. Kabos, and C. E. Patton, J. Appl. Phys. **75**, 1041-1046 (1994).

9. "Measurement of Spin Wave Instability Magnon Distributions for Subsidiary Absorption in Yttrium Iron Garnet Films by Brillouin Light Scattering," P. Kabos, G. Wiese, and C. E. Patton, Phys. Rev. Lett. **72**, 2093-2096 (1994).

10. "Brillouin Light Scattering on Fe/Cr/Fe Thin Film Sandwiches," P. Kabos, C. E. Patton, M. O. Dima, D. B. Church, R. L. Stamps and R. E. Camley, J. Appl. Phys. **75**, 3553-3563 (1994).

11. "Forward Volume Wave Microwave Envelope Solitons in Yttrium Iron Garnet Films - Propagation, Decay, and Collision," M. A. Tsankov, M. Chen, and C. E. Patton, J. Appl. Phys. **76**, 4274-4289 (1994).

12. "Backward Volume Wave Microwave Envelope Solitons in Yttrium Iron Garnet Films," M. Chen, M. A. Tsankov, J. M. Nash, and C. E. Patton, Phys. Rev. **B49**, 12773-12790 (1994).

13. "Theory of Magnetostatic Waves for In-plane Magnetized Isotropic Films," M. J. Hurben and C. E. Patton, J. Magn. Magn. Mat. **139**, 263-291 (1995).

14. "Microwave Envelope Soliton Threshold Powers and Soliton Numbers," J. M. Nash, C. E. Patton, and P. Kabos, Phys. Rev. **B**, in press (1995).

15. "Subsidiary Absorption Spin Wave Instability Processes in Yttrium Iron Garnet Thin Films - Coupled Lateral Standing Modes, Critical Modes, and the 'Kink' Effect," G. Wiese, P. Kabos, and C. E. Patton, Phys. Rev. **B**, in press (1995).

16. "Magnetostatic Wave Dynamic Magnetization Response in Yttrium Iron Garnet Films," M. A. Tsankov, M. Chen, and C. E. Patton, J. Appl. Phys., submitted (1995).

**2. Other Related Publications (no manuscripts or reprints filed):**

1. "High Power Microwave Pulse Generator," G. O. White, L. Chen, C. E. Patton, and R. L. Tinkoff, Rev. Sci. Instrum. **63**, 3156-3166 (1992).

2. "Frequency Dependence of the FMR Linewidth in Single Crystal Barium Ferrite Platelets," R. Karim, K. D. McKinstry, J. R. Truedson, and C. E. Patton, IEEE Trans. Magnetics **28**, 3225-3227 (1992).

3. "Effective Linewidth Due to Conductivity Losses at 10 GHz in Barium Ferrite," J. R. Truedson, C. E. Patton, and R. Karim, IEEE Trans. Magnetics **28**, 3309-3311 (1992).

4. "Comparison of Effective Linewidth and FMR Linewidth at 10 GHz in Ho Substituted YIG," J. R. Truedson, K. D. McKinstry, and C. E. Patton, IEEE Trans. Magnetics **28**, 3312-3314 (1992).

5. "Theory for the First-Order Spin-Wave Instability Threshold in Ferromagnetic Insulating Thin Films," G. Wiese, Z. Phys. **B 91**, 57 (1993).

6. "Growth and Characterization of High Purity Single Crystals of Barium Ferrite," M. A. Wittenauer, J. A. Nyenhuis, A. I. Schindler, H. Sato, F. J. Friedlaender, J. R. Truedson, R. Karim, and C. E. Patton, J. Cryst. Growth **130**, 533-542 (1993).

### D. List of Conference Digests and Abstracts and Other Presentations

Note: From May, 1993 through September, 1994, the Principal Inversigator was an IEEE (Institute of Electrical and Electronic Engineers) Magnetics Society Distinguished Lecturer.

1. "Microwave and Millimeter Wave Materials, Phenomena, and Devices." Workshop on Thin Film Materials, U.S. Army Research Office, Research Triangle Park, North Carolina, December 10, 1991.

2. "Numerical Solutions of the Nonlinear Schrödinger Equation for Microwave Solitons in Magnetic Thin Films," M. Chen, J. M. Nash, and C. E. Patton, INTERMAG Conference, April 13-16, 1992, St. Louis, Missouri.

3. "Workshop on Microwave Magnetics." Department of Condensed Matter Physics, Royal Institute of Technology, Stockholm, Sweden, May 18 - 28, 1992.

4. "Microwave Solitons in Magnetic Thin Films," Workshop - Application of Ferrite Films to Microwave and Millimeter Wave Devices, The 6th International Conference on Ferrites, Tokyo, Japan, September 29, 1992.

5. "Magnetic Modes in Anisotropic Thin Films - Critical Angles, Band Inversion, and Reentrant Modes, The 6th International Conference on Ferrites, Tokyo, Japan, September 30, 1992.

6. "Hexagonal Ferrite Research at Colorado State University," Office of Naval Research Workshop, Houston, Texas, November 30, 1992.

7. "Backward Volume Wave Solitons in a YIG Film," M. Chen, M. A. Tsankov, J. M. Nash, and C. E. Patton, 37th Conference on Magnetism and Magnetic Materials, December 1-4, 1992, Houston, Texas. (invited talk)

8. "Brillouin Light Scattering on Fe/Cr/Fe Films," M. O. Dima, D. B. Church, P. Kabos, and C. E. Patton, 37th Conference on Magnetism and Magnetic Materials, December 1-4, 1992, Houston, Texas.

9. "High Frequency Magnetic Excitations - Resonance, Spin-Wave Instability, and Solitons," IEEE Magnetics Society Distinguished Lecture.

   IEEE Magnetics Society Santa Clara Chapter, Hewlett Packard Research Laboratories, Palo Alto, California, May 18, 1993.
   Department of Electrical and Computer Engineering, University of California at Davis, Davis, California, May 21, 1993.
   Avionics Research Laboratory, GEC Marconi Research Centre, Chelmsford, United Kingdom, June 2, 1993.
   Department of Pure and Applied Physics, University of Salford, Salford, United Kingdom, June 7, 1993.
   Department of Physics, University of Colorado at Colorado Springs, Colorado Springs, Colorado, June 25, 1993.
   Naval Research Laboratory, Washington. DC, July 12, 1993.
   National Institute of Standards and Technology, Gaithersburg, Maryland, July 13, 1993.
   Army Research Laboratory, Ft. Monmouth, New Jersey, July 14, 1993.
   Department of Physics, Colorado State University, Fort Collins, Colorado, August 30, 1993.
   IEEE Denver Section Joint Meeting, Magnetics Society, Antenna Propagation Society, Microwave Theory and Techniques Society, Geoscience and Remote Sensing Society, Storage Technology Corporation, Louisville, Colorado, September 22, 1993.
   IEEE Magnetics Society Twin Cities Chapter, School of Electrical Engineering, University of Minnesota, Minneapolis, Minnesota, October 21, 1993.
   Materials Science Division, Argonne National Laboratory, Argonne, Illinois, October 27, 1993.
   Applied Mathematics Program, School of Engineering, University of Colorado at Boulder, Boulder, Colorado, November 5, 1993.
   College of Liberal Arts and Sciences, Okayama University, Okayama, Japan, December 6, 1993.
   Department of Physics, University of Guelph, Guelph, Ontario, Canada, January 12, 1994.
   Department of Physics, Oakland University, Rochester, Michigan, January 17, 1994.
   Department of Physics, Colorado School of Mines, Golden, Colorado, February 1, 1994.

2. Physikalisches Institut, Rheinisch-Westfälische Technische Hochschule Aachen, Aachen, Germany, March 17, 1994.
Experimentalphysik, Technische Hochschule Darmstadt, Darmstadt, Germany, March 18, 1994.
Institute of Molecular Physics, Russian Research Center "Kurchatov Institute," Moscow, Russia, March 23, 1994.
IEEE Magnetics Society Boston Chapter, Digital Equipment Corporation, Shrewsbury, Massachusetts, May 18, 1994.
Submillimeter Wave Technology Laboratory, University of Massachusetts Lowell, Lowell, Massachusetts, May 19, 1994.
Department of Physics and Astronomy, University of Georgia, Athens, Georgia, September 15, 1994.
National High Magnetic Field Laboratory, Florida State University, Tallahasse, Florida, September 16, 1994.
Joint IEEE Philadelphia Section and IEEE Magnetics Society Philadelphia Chapter Meeting, University of Pennsylvania, Philadelphia, Pennsylvania, September 20, 1994.

10. "Brillouin Light Scattering on Magnetic Excitations in Fe-Cr-Fe Sandwich Films," IEEE Magnetics Society Distinguished Lecture.

IBM Almaden Research Center, San Jose, California, May 19, 1993.
Department of Pure and Applied Physics, University of Salford, Salford, United Kingdom, June 8, 1993.
National Media Laboratory, 3M Center, St. Paul, Minnesota, October 22, 1993.
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois, October 26, 1993.
Department of Physics, Toho University, Chiba, Japan, December 2, 1993.
Institute for Materials Research, Tohoku University, Sendai, Japan, December 10, 1993.
Department of Electrical and Computer Engineering, Carnegie-Mellon University, Pittsburgh, Pennsylvania, January 14, 1994.
Institut für Festkörperforschung, Forschungszentrum Jülich, Jülich, Germany, March 16, 1994.
Department of Materials Science, Massachusetts Institute of Technology, Cambridge, Massachusetts, May 18, 1994.
Center for Materials for Information Technology, University of Alabama, Tuscaloosa, Alabama, September 19, 1994.

11. "Microwave Envelope Solitons in Magnetic Thin Films," IEEE Magnetics Society Distinguished Lecture.

School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota, October 31, 1993.
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois, October 25, 1993.
Department of Physics, Toho University, Chiba, Japan, December 2, 1993.
Department of Electrical Engineering, Nagoya University, Nagoya, Japan, December 7, 1993.
Westinghouse Research and Development Center, Pittsburgh, Pennsylvania, January 13,

1994.
Department of Physics, Ohio State University, Columbus, Ohio, January 18, 1994.
Puget Sound Space Center, Boeing Defense and Space Group, Kent, Washington,February 10, 1994.
Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada,February 11, 1994.
Department of Physics, University of California - Irvine, Irvine, California, February 15, 1994.
Department of Physics, University of California - San Diego, La Jolla, California, February 16, 1994.
Fachbereich Physik, Universität Osnabrück, Osnabrück, Germany, March 14, 1994.
P. L. Kapitza Institute for Physical Problems, Russian Academy of Sciences, Moscow, Russia, March 22, 1994.
Raytheon Research Division, Lexington, Massachusetts, May 19, 1994.
Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts, May 20, 1994.
National High Magnetic Field Laboratory, Florida State University, Tallahasse, Florida, September 16, 1994.
Center for Materials for Information Technology, University of Alabama, Tuscaloosa, Alabama, September 19, 1994.

12. "Microwave Measurement Techniques for Magnetic Materials," Department of Physics, Toho University, Chiba, Japan, November 30, 1993.

13. "Study of Magnetic Excitations by Brillouin Light Scattering," Department of Physics, Toho University, Chiba, Japan, December 1, 1993.

14. "Microwave and Millimeter Wave Magnetics - Status and Recent Developments," IEEE Magnetics Society Distinguished Lecture.

Department of Physics, Toho University, Chiba, Japan, December 1, 1993.
Tokyo Chapter of the Magnetics Society of Japan, Nihon University, Tokyo, Japan, December 3, 1993.
Institut für Experimentalphysik III, Ruhr-Universität Bochum, Bochum, Germany, March 15, 1994.
St. Petersburg Electrotechnical University, St. Petersburg, Russia, March 21, 1994.
Institute of Radioengineering and Electronics, Russian Academy of Sciences, Moscow, Russia, March 24, 1994.

15. "Brillouin Light Scattering Study of Second Order Spin Wave Instability Processes in Yttrium Iron Garnet Films," P. Kabos, G. Wiese, A. D. Sullins, and C. E. Patton, Sixth Joint MMM-INTERMAG Conference, June 20-23, 1994, Albuquerque, New Mexico.

16. "Brillouin Light Scattering on Thick fcc Cobalt Films," M. Mendik, P. Kabos, and C. E. Patton, Sixth Joint MMM-INTERMAG Conference, June 20-23, 1994, Albuquerque, New Mexico.

17. "Magnetostatic Wave Dynamic Magnetization Amplitude Response in Yttrium Iron Garnet Films at High Microwave Power Levels," M. A. Tsankov, M. Chen, and C. E. Patton, Sixth Joint MMM-INTERMAG Conference, June 20-23, 1994, Albuquerque, New Mexico.

18. "Microwave Envelope Solitons in Magnetic Thin Films." Joint meeting of the Antenna and Propagation, Microwave Theory and Techniques, and Geoscience and Remote Sensing Societies of the IEEE, National Institute of Standards and Technology, Boulder, Colorado, February 23, 1995.

19. "Spin Wave Instability Magnon Distribution for Parallel Pumping in Yttrium Iron Garnet Films," P. Kabos, M. Mendik, G. Wiese, and C. E. Patton, INTERMAG 95, April 18-21, 1995, San Antonio, Texas.

20. "Green's Function and Scalar Potential Dipole-Exchange Spin Wave Dispersion Calculations for Magnetic Thin Films," M. Chen, H. Yu, and C. E. Patton, INTERMAG 95, April 18-21, 1995, San Antonio, Texas.

21. "Brillouin Light Scattering in Fe/Cr/Fe Thin Film Sandwiches," M. Mendik, P. Kabos, C. E. Patton, and R. L. Stamps, INTERMAG 95, April 18-21, 1995, San Antonio, Texas.

22. "Reflection and Collision of Backward Volume Wave Microwave Envelope Solitons in Yttrium Iron Garnet Films," N. G. Kovshikov, B. A. Kalinikos, J. M. Nash, and C. E. Patton, INTERMAG 95, April 18-21, 1995, San Antonio, Texas.

23. "Phase Profiles for Microwave Magnetic Envelope Solitons," J. M. Nash, P. Kabos, and C. E. Patton, INTERMAG 95, April 18-21, 1995, San Antonio, Texas.

24. "Subsidiary Absorption Spin Wave Instability Butterfly Curve Size Effects and Lateral Modes in Yttrium Iron Garnet Films," G. Wiese, P. Kabos, and C. E. Patton, INTERMAG 95, April 18-21, 1995, San Antonio, Texas.

## E. List of Participating Scientific Personnel

### 1. Senior Personnel:

| | |
|---|---|
| Dr. Carl E. Patton | Principal Investigator |
| Dr. Mincho A. Tsankov | Visiting Scientist |
| Dr. Pavel Kabos | Visiting Scientist |
| Dr. David Franklin | Visiting Scientist |
| Dr. Boris Kalinikos | Visiting Scientist |
| Dr. Nikolai Kovshikov | Visiting Scientist |

### 2. Postdoctoral and Graduate Student Personnel:

| | |
|---|---|
| Dr. Garrelt Wiese | Postdoctoral Research Fellow |
| Dr. Razoul Karim | Postdoctoral Research Fellow |
| Dr. Ming Chen | Graduate Student and Ph.D. Candidate; Ph.D., 1992; Postdoctoral Research Fellow |

| | |
|---|---|
| Dr. Kevin D. McKinstry | Graduate Student and Ph.D. Candidate; Ph.D., 1992; Postdoctoral Research Fellow |
| Dr. Michael Mendik | Postdoctoral Research Fellow |
| Mr. John R. Truedson | Graduate Student and Ph.D. Candidate; Ph.D., 1993 |
| Mr. Jon M. Nash | Graduate Student and Ph.D. Candidate |
| Mr. Mike O. Dima | Graduate Student and Ph.D. Candidate |
| Mr. Michael Hurben | Graduate Student and Ph.D. Candidate |
| Mr. Richard G. Cox | Graduate Student |
| Mr. Ian Caiozzi | Graduate Student |
| Mr. Cort Gautier | Graduate Student |
| Ms. Sandra Ball | Graduate Student |
| Mr. Hans Nicolas | Fachhochschule Regensburg - Practical training |
| Mr. Joseph Hausladen | Fachhochschule Regensburg - Practical training |
| Mr. Christian Betz | Fachhochschule Regensburg - Practical training |
| Mr. Stephan Bischoff | Fachhochschule Regensburg - Practical training |
| Mr. Thomas Semmelman | Fachhochschule Regensburg - Practical training |

**3. Undergraduate and High School Student Personnel:**

| | |
|---|---|
| Mr. Daniel Church | Physics Major; B.S. 1991; Research Associate |
| Mr. Roger Tinkoff | Physics Major and Merit Work Study Student, B.S., 1994 |
| Mr. Toby Carrol | Physics Major and Merit Work Study Student; B.S., 1994 |
| Mr. Eric Wright | Physics Major and Merit Work Study Student; B.S., 1995 |
| Mr. Allan Sullins | Physics Major and Merit Work Study Student; B.S., 1995 |
| Mr. Theodore Bushanam | Electrical Engineering Major, Senior Project Research; B.S., 1995 |
| Mr. Benjamin Greigo | High School Student (REAP Program); Mechanical Engineering Major - Stanford University |
| Mr. Lucas Buxman | High School Student (REAP Program) |
| Mr. Neal Rakow | High School Student (REAP Program) |
| Mr. Andy Eberhard | High School Student (REAP Program); Mechanical Engineering Major - University of Colorado |
| Mr. Matthew Quint | High School Student (REAP Program) |
| Mr. Justin Ward | High School Student (REAP Program) |
| Ms. Hong Yu | High School Student (REAP Program) |

## REPORT OF INVENTIONS

Microwave Magnetic Soliton Oscillator
Ming Chen, Mincho A. Tsankov, Carl E. Patton
(Invention Disclosure April 28, 1994)

Parametric Microwave Magnetic Soliton Amplifier
Pavel Kabos, Garrelt Wiese, Jon M. Nash, Carl E. Patton
(Invention Disclosure September 22, 1994)